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USING GIS TO ESTIMATE THE AVALANCHE RELEASE HAZARD LEVEL: THE CASE OF KASPROWY WIERCH, TATRA MTS

ZASTOSOWANIE GIS W TYPOLOGII OBSZARÓW POTENCJALNEGO WYSTĘPOWANIA LAWIN ŚNIEŻNYCH NA PRZYKŁADZIE REJONU KASPROWEGO WIERCHU W TATRACH

Paweł Chrustek

Jagiellonian University, Department of Climatology, Cracow, Poland

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Introduction

Issues concerning snow avalanches have interested scientists for a long time. Because of complexity of the subject, avalanches are examined by interdisciplinary research groups. In countries where mountains cover a large part of the terrain, avalanche issues are becoming very important. Their destructive element brings not only casualties, but also significant infrastructure damage.

In the Tatra Mountains avalanches are less serious because of the relatively small area covered by mountains and a lack of inhabited areas. This does not mean that it is not important. Each year in the Tatra Mountains brings a few fatal accidents caused by avalanches. The greatest tragedy took place on 28th January 2003, when an avalanche in the Mount Rysy area killed seven high school students.

Systematic snow and avalanche measurements were initiated in 1959 by Chomicz. In 1960, snow and avalanche measurements were added to the climate research programme performed by the State Hydrological and Meteorological Institute (PIHM) at a snow measurement station, located on Hala Gasienicowa. The measurements were made according to guidelines created by Chomicz (1963).

Observation results collected for many years, recording the number, occurrence, area and size of avalanches, has allowed for the creation of a map of avalanche locations and frequency in the Tatra Mountains. Data about avalanches were published in the sixties by PIHM in "Śnieg i lawiny w Tatrach" *(Snow and avalanches in the Tatra Mountains)*. Another result of this research was the dissertation „Instrukcja do prognozowania Lawin Śnieżnych w Tatrach Polskich” *(Instruction for forecasting avalanches in the Tatra Mountains)*, by Kłapowa (1989).

In the mid eighties, economic reasons led to a reduction in the measurements programme. The station was functioning as a meteorological station, with observations of snow cover reduced to minimum. However, once a week an announcement for skiers was issued, as well as daily avalanche warnings based on the guidelines mentioned above. These announcements were transferred to the Voluntary Mountain Rescue Service (TOPR) (Chrustek, 2005).

At present, research is performed by the Avalanche Forecast Team of the Institute of Meteorology and Water Management (IMGW – former PIHM), cooperating closely with the mountain rescue service. Teams are working on an adaptation and implementation of the SAFRAN – CROCUS – MEPRA (SCM) models, which enable determination of avalanche hazard level for avalanches caused naturally or triggered by humans. These models were created at CEN (Centre d’Etudes de la Neige – the Snow Study Centre) in Grenoble for the French Alps and Pyrenees.

GIS technology is widely used for research on snow avalanches, mainly for creating avalanche risk maps. According to the literature, 65% of such maps in Europe were created using GIS (Ghinoi, 2003).

In research performed in Poland, only traditional methods were used to create avalanche risk maps. This use of digital techniques and GIS modeling is the first attempt, not only for the study area, but also for the whole Polish area (Chrustek, 2005).

The goal of this study is to determine Potential Release Areas (PRA) in the research area and their typology, depending on the Avalanche Release Hazard Level (ARHL). As mentioned above, it is the basis for creating synthetic analysis and avalanche risk maps.

Study area

The study area comprises 1448 ha in surface area, some 3,6 km north to south and 5,6 km east to west. Topographically, the study area is located near the Sucha Stawianska Valley (1.8 ha in area, located east from Mount Kasprowy Wierch) and the upper part of the Bystra Valley (1446.2 ha in area, north-west from Mount Kasprowy Wierch).

Kasprowy Wierch is characterized by frequent avalanches, because of the specific morphology (long, steep slopes). Dense tourist infrastructure in this area (mountain hostels, ski lifts, ski slopes) results in high tourist activity, which increases the risk of accidents involving people.

According to Hess (1965), the study area is situated within four vertical climatic zones (based on mean monthly temperature, Ta): moderate cool ($4^0C \leq Ta < 6^0C$), cool ($2^0C \leq Ta < 4^0C$), very cool ($0^0C \leq Ta < 2^0C$) and moderate cold ($-2^0C \leq Ta < 0^0C$). The mean vertical temperature gradient is $0,5^0C/100$ m and the greatest annual rainfall sum exceeds 1850 mm. The rainfall maximum occurs in June, the minimum in October-February (for the highest parts of the mountains) or in September-November (in the lower parts). Almost half the precipitation falls as snow and the highest parts of the mountains receive snowfall each month. Snow cover on Mt. Kasprowy Wierch is observed between the end of September and the end of June, with a mean maximum depth (over 160 cm) at the end of March (Trepińska, 2002).

Methodology

The method to determine ARHL in PRAs proposed by the author of this study is based on raster analysis of selected avalanche factors (constant: inclination, land cover, terrain shape; and variable: wind, amount of direct solar radiation) (Chrustek, 2005). The impact and correlation of the chosen factors was introduced by describing generated analytic layers.

Each month in which there is an avalanche risk was analyzed separately because of a large variability of the parameters for the chosen factors, throughout a year, as well as seasonal changes of their impact on avalanche occurrence. The research, therefore, focused on the months between November and May.

The method consists of three steps:

1. Generating analytic layers,
2. Quantifying layers,
3. Generating Summary Maps.

Generating analytic layers

SLOPE LAYER, a single layer for all months, contains forest-free terrains with slope inclination between 30 and 60 degrees. It was generated from a 10m resolution DEM. The DEM parameters and range of slope angles was determined from a SLF/WSL scientists' analysis for Davos (Gruber et al., 2002). All maps used and generated in the analysis are for UTM zone 34N, using reference ellipsoid WGS84.

LANDFORMS LAYER, a single layer for all months, classifies the slope crosswise profiles into three classes: concave forms, flat forms and convex forms. The layer was generated using a 50 m resolution DEM, the parameters based on analysis from Davos (Gruber et al., 2002). Slope topography in longitudinal and cross section has an impact on tension state in the snow pack and on the size of the possible snow accumulation. Generally, avalanches are more frequent on slopes with a concave cross profile, which is directly connected to snow accumulation capacity and the forces generated in the snow pack (gulleys, ravines). Flat slopes have a smaller accumulation capacity, but create favourable conditions for slab avalanches. Convex slopes have the least avalanche potential (McClung and Schaerer, 2002).

LANDCOVER LAYER, a single layer for all months, contains land cover divided into five classes: forest, dwarf mountain pine, rocky slope, areas within shadow, determined photgrammetrically, and mountain meadow. Areas inside the shadow class are included in the analysis because, during the local visits, it was established that those areas consist of mainly rocky slopes, with partial cover of dwarf mountain pine. Forests are excluded because avalanches are not released in such areas.

Land cover mostly influences bonding between the snow pack and the surface. Forests stabilize the snow pack, increasing friction and its stability, resulting in avalanche prevention, provided the forest has a specific density. Areas with isolated trees have significantly less impact in stabilizing the snow pack. However, snow pack stabilization is important only for avalanche release in a given area: forests located below areas of avalanche release, regardless of forest density and quality, are unable to stop the moving snow masses.

A similar stabilizing role is characteristic for some bushes and rocky areas (Kłapowa, 1980). Their role becomes very small when they are completely covered with snow. Mountain grass increases the probability of avalanche release and is especially prone to snow accumulation: its properties create a gliding layer.

MODEL SHADOW LAYER, one layer for each month. These layers show areas contained in average monthly shadow cast by highlands. Mean shadow values were calculated based on DEM analysis, using mean monthly sun azimuth and altitude values. Heat conductivity through snow cover is an important avalanche factor, causing physical change in the snow crystals. One of the changes produces depth hoar: the result of a vertical temperature gradient in the snow cover larger than 10 degrees Celsius (McClung and Schaerer, 2002). Although this process is quite slow, a couple of days of freezing temperature results in the creation of a depth hoar layer, similar to a surface hoar layer, which might destabilize and weaken the snow cover. Depth hoar is mainly created in continental climate conditions and places characterized by small amount of solar energy, such as areas in shadow.

Slopes characterized by a large amount of direct solar energy, regular intervals of cooling and heating, result in quick bonding and snow pack stabilization (McClung and Schaerer, 2002).

WIND ASPECT LAYER, one layer for each month. These layers are based on leading wind direction analysis for the study area. Meteorological data were obtained from the high-mountain meteorological station located on Mount Kasprowy Wierch ($\varphi = 49^0$ 13' 57"N; $\lambda = 19^0$ 58' 55"E; H = 1987 a.s.l.). Percentage frequency of wind occurrence for each direction was calculated, based on summarized data recorded between 1984 and 2004. These calculations were used to determine terrain exposure to wind direction, identifying the lee side slopes and luff side slopes. Wind is responsible for transport and redistribution of snow; it has a very significant impact on uneven distribution of snow cover. If the wind blows across a mountain ridge, it creates large pressure on the luff side slope, creating a hard snow surface. Snow not bonded to the surface is thrown through the ridge to the other side, which leads to creating the potential for slab avalanche (Trepińska, 2002).

Quantifying layers

Layer quantifying involves assigning the specific numeric value for each of the analyzed factors, while preserving time and location. It is assumed, that the quantifier grows linearly and proportional to the impact of the given avalanche factor. Analysis was performed using the raster layers generated in the previous stage, considering the monthly differences from November to May. Before quantifying, each layer was divided into the following classes:

Landforms layer

a) convex landform
b) flat landform
c) concave landform

Land cover layer

a) dwarf mountain pine
b) rocky slope
c) areas inside shadow class
d) mountain meadow

Wind Aspect layers (based on mean wind direction)

a) class one – lee side slopes, according to the most frequent wind directions for the given month.
b) class two – lee side slopes, according to the second most frequent wind directions for the given month.
c) class three – lee side slopes, according to the third most frequent wind directions for the given month.

d) class four – all other lee side slopes according to the wind directions in the given month.

Model Shadow layers

a) area inside shadow

b) area outside shadow

The following equation was used for assigning quantifiers to these classes:

Quantifier = (12/LK) · NK · WW

where:

12 – constant being highest common denominator for the number of classes in individual layers,

LK – the number of classes in the individual layer,

NK – class number,

WW – layer weight.

Assigning layer specific weight (WW) and class number (NK) is connected with the varying impact of the given factor on possible avalanche release. Factor impact is variable, changes over time, and is unique to a given mountain range. This results in assigning a value from 1 to 4 to each four analyzed layers, and assigning a suitable class number to each class (as mentioned earlier, layer weight and class number increases according to the impact on avalanche release probability).

Landforms, within a specific inclination value range, have the biggest impact on avalanche formation (Ghinoi, 2003), so these are assigned the largest weight (WW=4), for all analysed months.

For each analyzed month, tables were prepared showing layers grouped according to the layer weight and class number (Tab.1). Using the equation shown above, corresponding quantifiers were calculated for each analyzed class. Varying impact of the factors, through changing snow conditions throughout the winter, for avalanche formation was taken into account when calculating the quantifiers.

This gives the base for preparing the complete set of layers for each month, where each class was assigned the calculated value – quantifier. It means that each pixel included in the corresponding class has calculated value, common for the whole class.

Table 1. Example of quantifying layers for November

Land-form	WW = 4	NK	Land cover	WW = 3	NK	Wind Aspect	WW = 2	NK	Model shadow	WW = 1	NK
Concave	16	1	dwarf mountain pine	9	1	others	6	1	outside	6	1
Flat	32	2	rocky slope	18	2	S,SE	12	2	inside	12	2
Convex	48	3	shadow	27	3	NE	18	3	–	–	–
–	–	–	mountain meadow	36	4	N	24	4	–	–	–

Generating Summary Maps

In the last part of the study, summary raster maps were created for each month. Layers with specific quantifiers were summed together. Finally, summary raster maps were reclassified to give four classes by division of the value range using the equal interval criterion. This allowed the generation of maps indicating avalanche release risk for a given area for each month. The Avalanche Release Hazard Level (ARHL), risk, value was defined as one of four classes: moderate, considerable, high and very high.

Final Maps

From this complex analysis of the avalanche forming factors, seven raster maps were generated, showing ARHL, for each month between November and May. One of those maps is shown on Figure 1. The percentage of areas with a given Avalanche Release Hazard Level, for each month, shown at Figure 2.

From analysis of historical avalanche release in the study area, using data from the Tatra National Park and the Institute of Meteorology and Water Management, it was determined that among 108 analyzed release points, 91 are within the generated PRA. Most of them, 43, are within concave land forms, 28 within flat land forms, and the least, 20, within convex land forms.

Table 2. Avalanche Release Hazard Level in historical avalanche release point

	Example 1 13.02.1960	Example 2 29.03.1960	Example 3 09.03.2001	Example 4 12.04.2003	Example 5 12.04.2003	Example 6 31.01.2004
ARHL	Class 3 (high)	Class 3 (high)	Class 2 (moderate)	Class 4 (very high)	Class 4 (very high)	Class 3 (high)

The results were also verified by analyzing a few examples of historical avalanches, where occurrence date is known, giving the ability to assign the case to the ARHL layer from the corresponding month. The hazard levels for avalanche release for these specific cases are shown in Table 2.

Discussion and conclusions

The method described for evaluating Avalanche Release Hazard Level (ARHL) in the Potential Release Areas (PRA) is the first attempt of such kind for the study area of Mount Kasprowy Wierch. However, the results seem to be satisfying.

The use of GIS in the analysis enables a rapid interactive questioning process, thus allowing savings in cost and time (Widacki, 1997).

The output maps show ARHL with the monthly average, which can be controversial, as the hazard level changes quickly in time. However, the dominant parameter in the analysis is terrain inclination and form, which are both constant. We can also assume that land cover can be treated as a constant. Shadow areas vary throughout the day, but by analyzing physical changes in the snow cover, which are normally considered to operate over a long term, it is safe to assume that the monthly integration interval is sufficient.

The most variable factor is wind direction. It is obvious that strong winds and heavy snowfalls can fundamentally change the avalanche hazard. Because there is a seasonal air circulation pattern which can be observed, changes in this factor were also integrated to monthly period. It is clear that air circulation in mountain range is very changeable, depending on landforms. There are also significant daily circulation changes present, which have to be considered in any proposed methods. To develop these methods for daily monitoring would require additional models of air flows in the mountain range, to provide precise information on air flow change according to terrain and height.

The goal of the quantifying layers method was to indicate, as simply as possible, the ratio between the weight of specific layers, as it changes through the season. Weighing is arbitrary and based on knowledge about the time/space factor changes and their impact on avalanche formation. These changes are usually unique for a given mountain range, which results in need for additional analysis of snow and climate factors. Weights were also evaluated considering the fact that the most important impacts on avalanche formation are terrain morphology and the factors responsible for bonding the snow cover to the surface (Ghinoi, 2003).

Further development of these methods requires the calculation of dynamic models allowing modelling the avalanche run out zones. This would allow for determining complex avalanche hazard areas. Joining such maps with avalanche forecast models, e.g. SAFRAN-CROCUS-MEPRA chain, would improve existing monitoring and warning systems. It appears that graphic presentation, showing the geographic distribution of the hazard areas, can be much more effective medium than table or textural descriptions.

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Abstract

Issues concerning avalanches have interested scientists for a long time. Because of the complexity of the subject, avalanches are examined by interdisciplinary research groups. GIS technology has been broadly used for such research, mainly for creating maps indicating avalanche hazard levels. The basis for creating such maps is determining Potential Release Areas (PRA), which is one of main goals of this study.
Additionally, in any PRA, analysis of factors that can cause avalanche release, such as landform, land cover, amount of direct solar energy, or main wind directions for a given area, led to the determination of average monthly Avalanche Release Hazard Level (ARHL) shown on seven raster maps, for each month from November to May. This study proposes a new methodology for this analysis.
This methodology was used to predict avalanche release areas and their typology for the study area in the Tatra mountains. Analysis of historical avalanche release points showed that, among 105 research points, 91 are within the generated PRA units, which gives 85% correlation, which seems to give satisfactory results.

Streszczenie

Problematyka lawin od dawna interesowała badaczy. Ze względu na złożoność problemu, badaniem lawin zajmują się zwykle interdyscyplinarne zespoły badawcze. Technologia GIS znalazła szerokie zastosowanie w owych badaniach, głównie przy tworzeniu map zagrożenia lawinowego. Podstawą przy opracowywaniu owych map jest wyznaczenie obszarów potencjalnego występowania lawin śnieżnych (Potential Release Areas – PRA), które jest jednym z głównych celów opracowania.
Dodatkowo w wyznaczonych obszarach PRA, poprzez analizę wpływu czynników lawinotwórczych (takich jak: forma terenu, pokrycie terenu, wielkość dopływu bezpośredniej energii słonecznej, czy przeważające kierunki wiatrów na badanym obszarze), określono średni miesięczny stopień zagrożenia uwolnienia lawiny (Avalanche Release Hazard Level – ARHL), przedstawiony na siedmiu mapach rastrowych (dla miesięcy od listopada do maja). Do wykonania tych analiz wykorzystano własną nową metodę.
Analizując historyczne punkty obrywu lawin na badanym terenie, określono, że spośród 108 analizowanych punktów obrywu, aż 91 zawiera się w granicach wygenerowanych jednostek PRA, co daje 85% zgodność lokalizacji.
Przedstawiane metody określania obszarów potencjalnego występowania lawin i ich typologia są pierwszą tego typu próbą na badanym obszarze. Wyniki weryfikacji sporządzonej na podstawie danych o historycznych lawinach zdają się być zadowalające.

mgr Paweł Chrustek
pchrustek@geo.uj.edu.pl
http://www.klimat.geo.uj.edu.pl

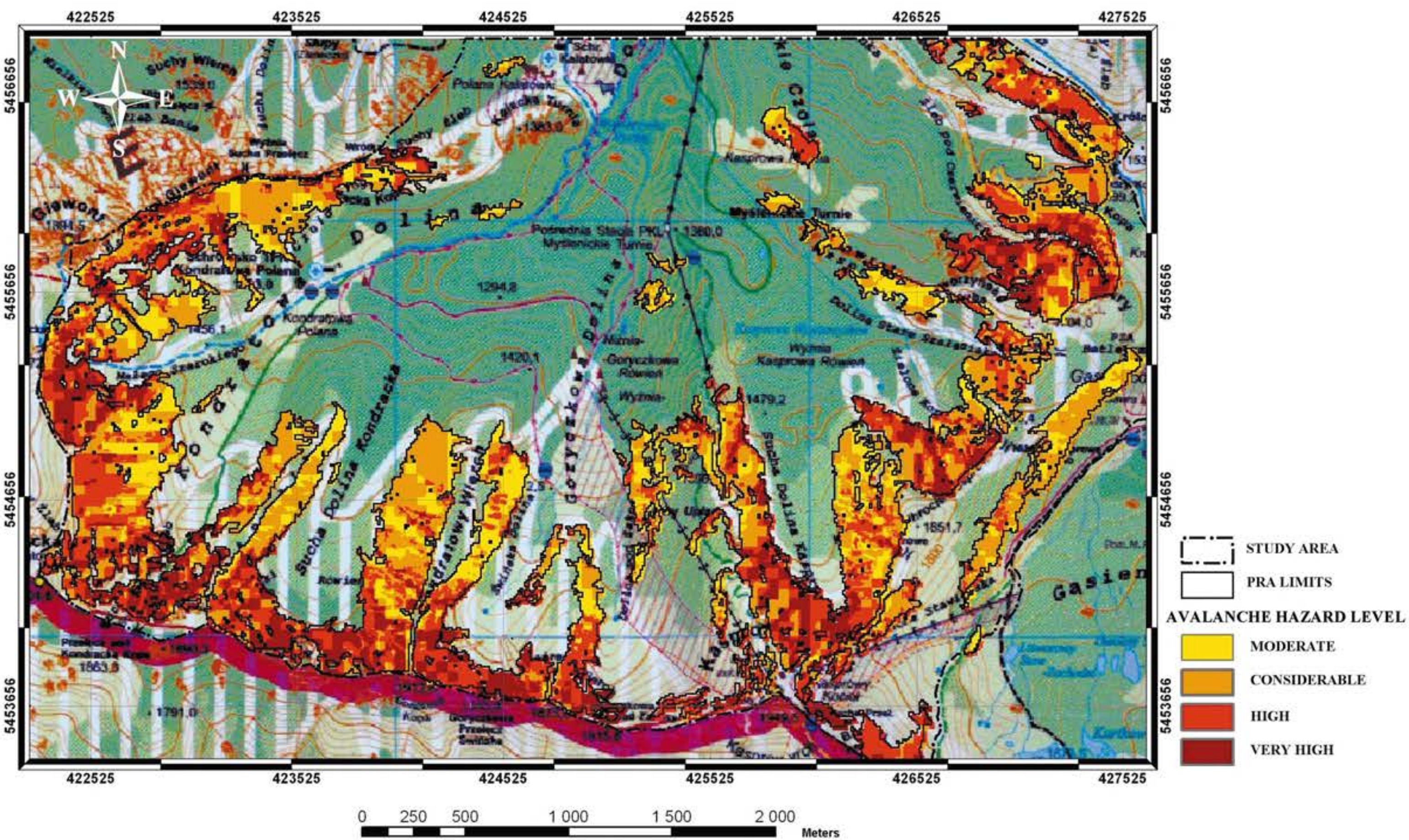

Figure 1. Avalanche Release Hazard Level map for November (in the background – tourist map WZKart scale 1:30 000)

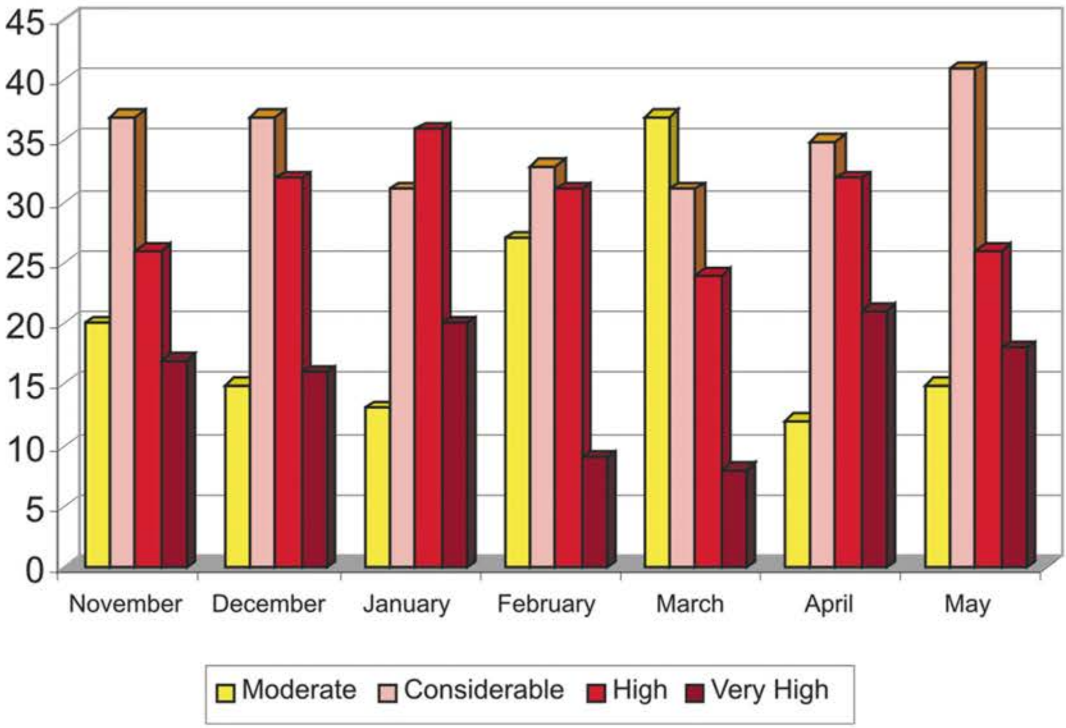

Figure 2. Percentage of areas with given Avalanche Release Hazard Level, for each month